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Title: Double Beta Decay: Is the Neutrino Mass within Reach?

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Double Beta Decay: is the neutrino mass within reach

- Neutrinos
- Science of $\beta\beta$
- MAJORANA Demonstrator

Why Neutrinos?



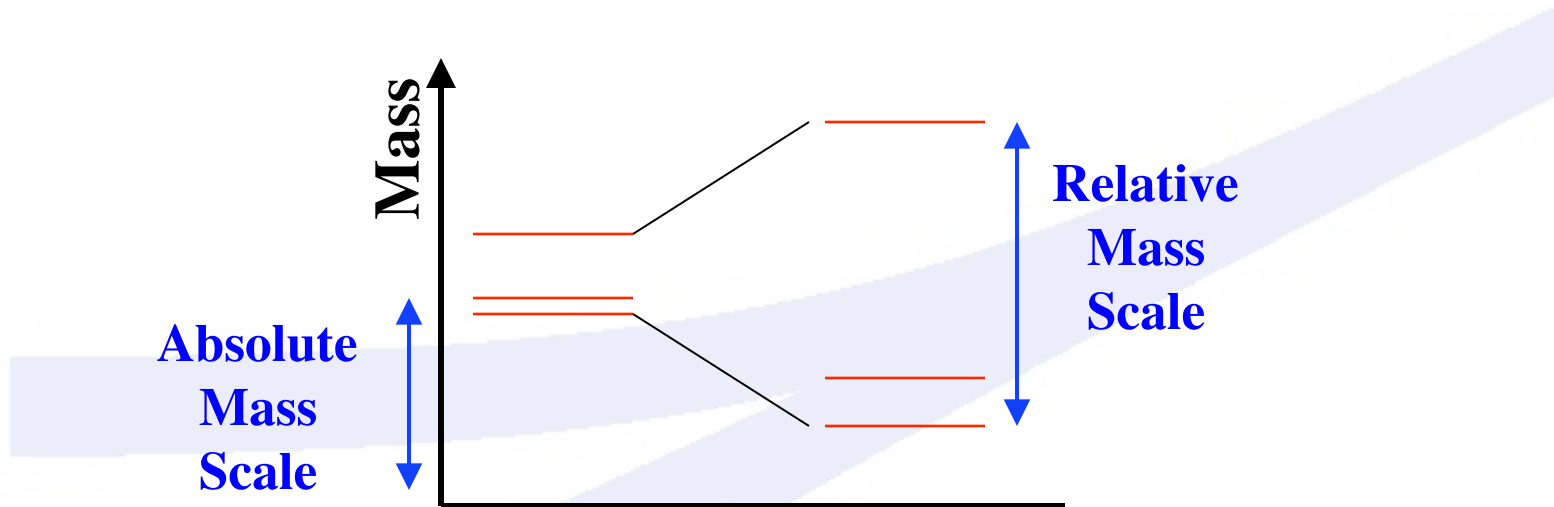
- **properties are critical input to many physics questions**
- **Particle/Nuclear Physics**
 - Fundamental questions about standard model
 - Fundamental issues regarding interactions
- **Cosmology**
 - Large scale structure
 - Leptogenesis and matter-antimatter asymmetry
- **Astrophysics**
 - Supernova explosions
 - Solar burning



Why are neutrinos unusual?

- **Because the neutrino only interacts weakly, it is a very difficult particle to study. We don't know much about it.**
- **Neutrinos might be the ultimate neutral particle**
 - They would not be distinct from their antiparticles.
 - If so they would be Majorana particles
- **They might also be Dirac particles**
 - Like the charged quarks and leptons
- **The difference between these two possibilities greatly influences how the neutrino is incorporated into the Standard Model**

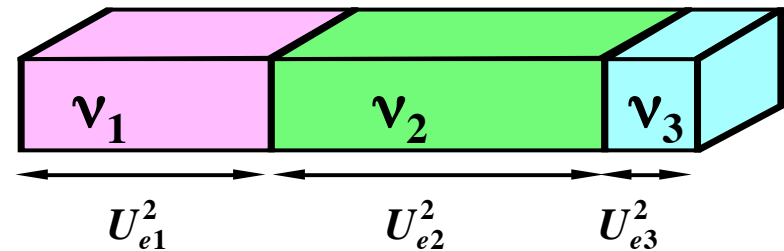
Neutrinos: What do we want to know?



Dirac or Majorana

$$\begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \\ \bar{\nu}_{\downarrow} \\ \bar{\nu}_{\uparrow} \end{pmatrix} \text{ or } \begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \end{pmatrix}$$

ν_e



Mixing



Neutrino Masses: What do we know?

- The results of oscillation experiments **indicate ν do have mass!**, set the relative mass scale, and a minimum for the absolute scale.
- β decay experiments set a maximum for the absolute mass scale.

$$50 \text{ meV} < m_\nu < 2200 \text{ meV}$$

We also know ν mix.



The weak interaction produces ν_e, ν_μ, ν_τ .

These are not pure mass states but a linear combination of mass states.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

**Oscillation experiments indicate
that ν mix and constrain $U_{\alpha i}$.**



The Standard Model Particles

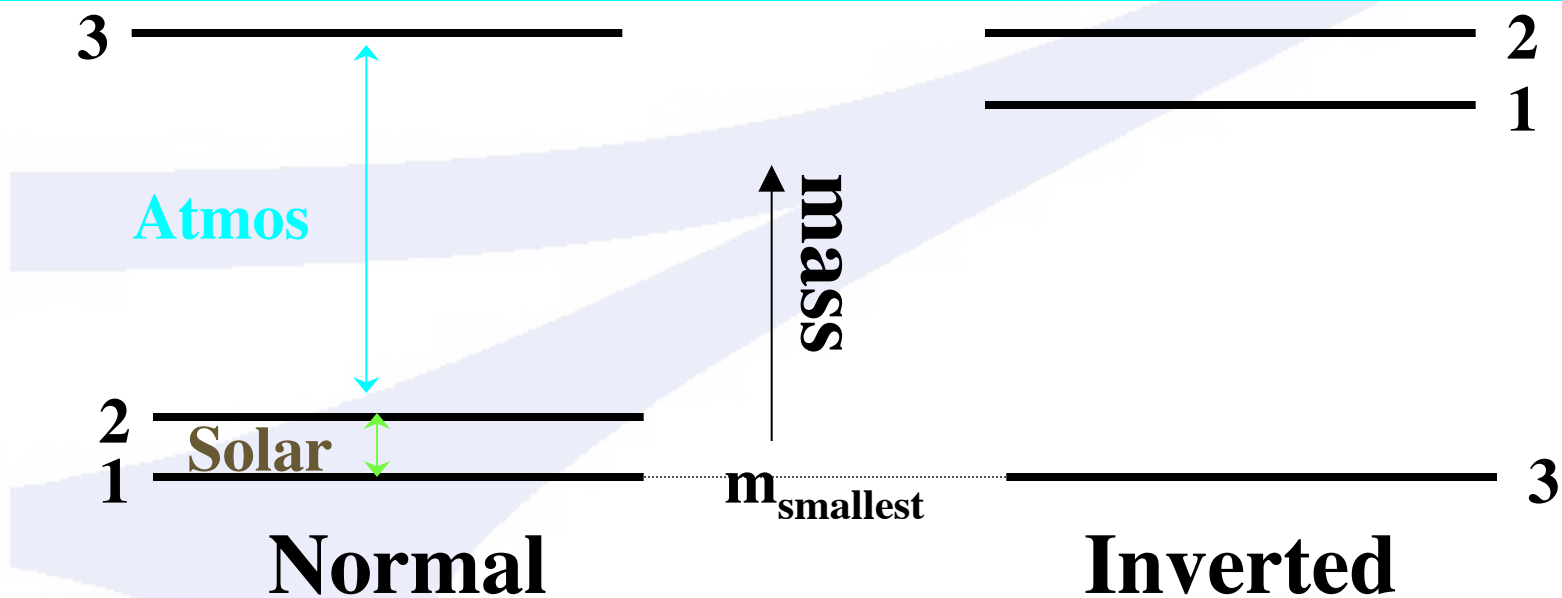
Quarks	u up	c charm	t top	γ gamma
	d down	s strange	b bottom	g gluon
Leptons	ν_3	ν_1	ν_2	W W boson
	e electron	μ muon	τ tau	Z Z boson

The Neutrinos

Force Carriers



Oscillations and Hierarchy Possibilities

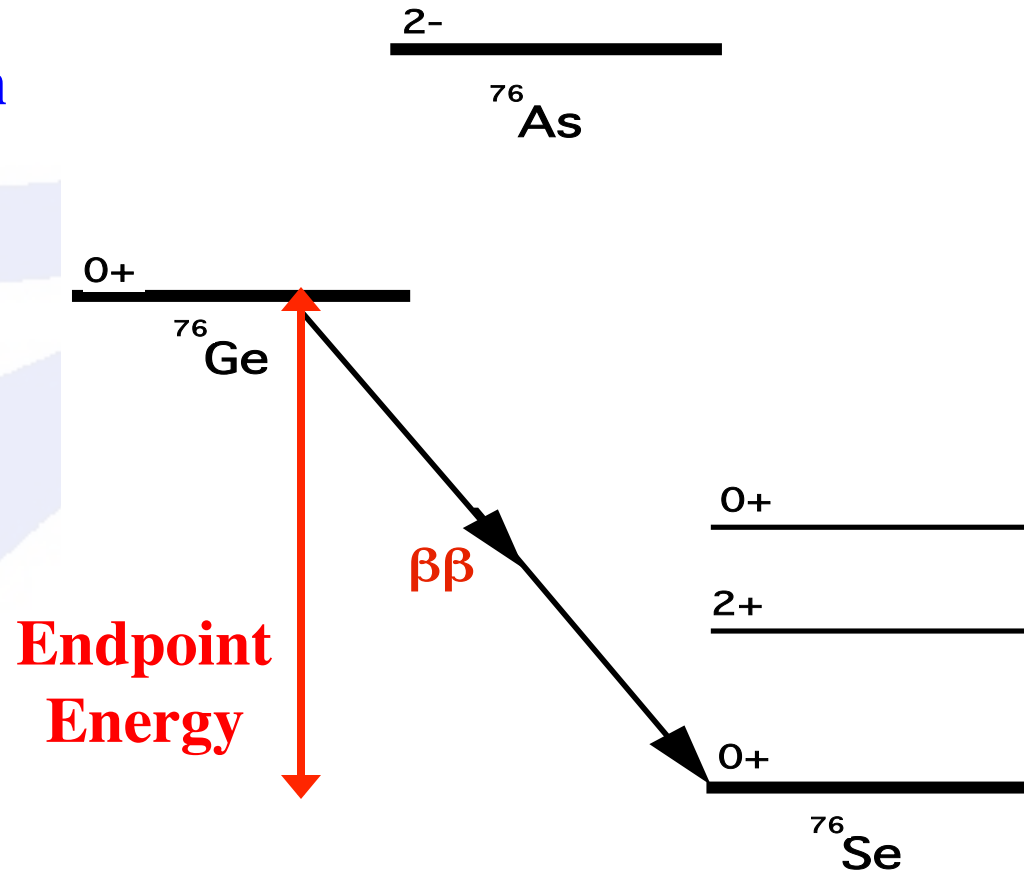


ν_e is composed of a large fraction of ν_1 .

Example $\beta\beta$ Decay Scheme



In many even-even nuclei, β decay is energetically forbidden. This leaves $\beta\beta$ as the allowed decay mode.





What is $\beta\beta$?

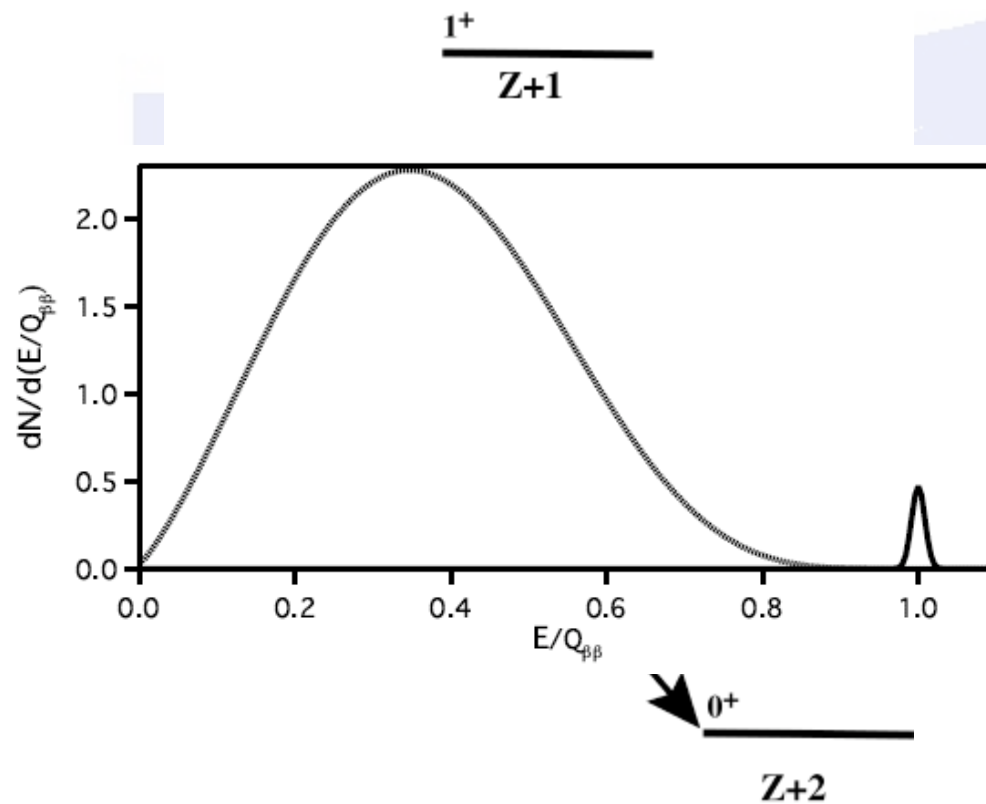


Fig. from arXiv:0708.1033

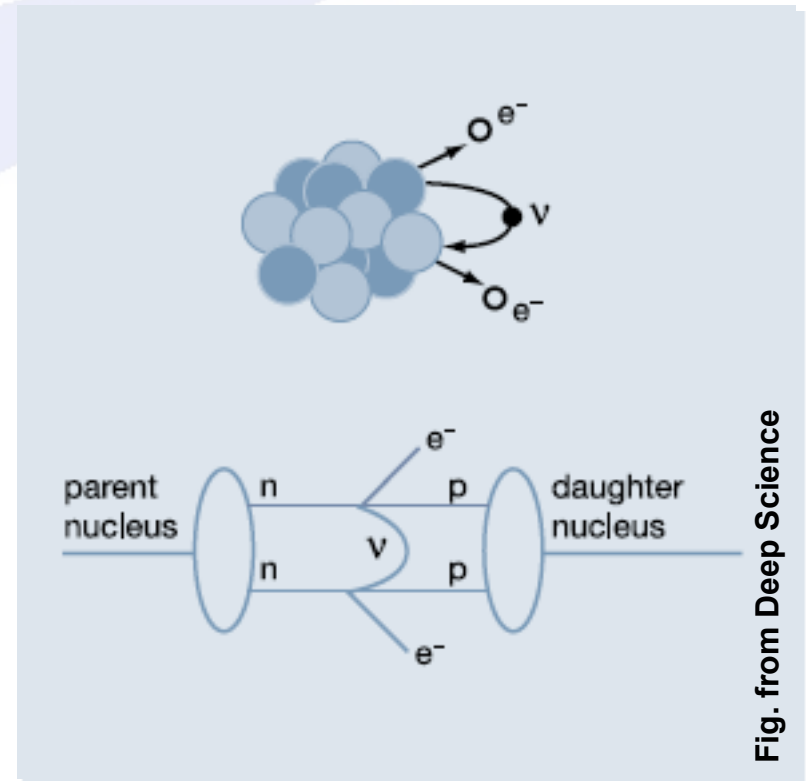


Fig. from Deep Science



$\beta\beta$ Decay Rates

$$\Gamma_{2\nu} = G_{2\nu} |M_{2\nu}|^2$$

$$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 m_\nu^2$$

G are calculable phase space factors.

$$G_{0\nu} \sim Q^5$$

|M| are nuclear physics matrix elements.

Hard to calculate.

m_ν is where the interesting physics lies.



What about mixing, m_ν & $\beta\beta(0\nu)$?

No mixing: $\langle m_{\beta\beta} \rangle = m_{\nu_e} = m_1$

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^3 |U_{ei}|^2 m_i \varepsilon_i \quad \text{virtual } \nu \text{ exchange}$$

$\varepsilon = \pm 1$, CP cons.

Compare to β decay result:

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^3 |U_{ei}|^2 m_i^2}$$

**real ν
emission**

Compare to cosmology:

$$\Sigma = \sum m_i$$



What can be learned from Oscillations & $\beta\beta$?

- **From oscillations, we have:**
 - Information on U_{ei}
 - Information on δm^2
- **With $\langle m_{\beta\beta} \rangle$ constraints, we can constrain m_1 : (2 flavor example)**

$$\langle m_{\beta\beta} \rangle = U_{e1}^2 m_1 + \varepsilon_{21} U_{e2}^2 \sqrt{m_1^2 + \delta m_{21}^2}$$

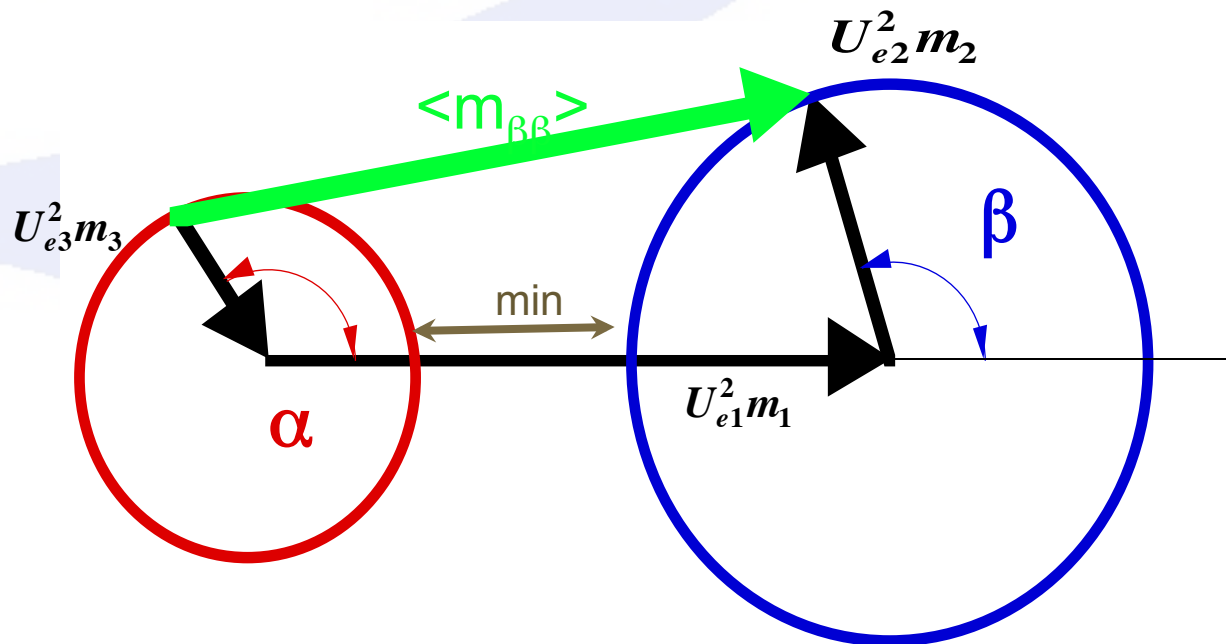


Min. $\langle m_{\beta\beta} \rangle$ as a vector sum. General Case

$$\langle m_{\beta\beta} \rangle = \left\| U_{e1}^2 m_1 + e^{i\beta} U_{e2}^2 m_2 + e^{i\alpha} U_{e3}^2 m_3 \right\|$$

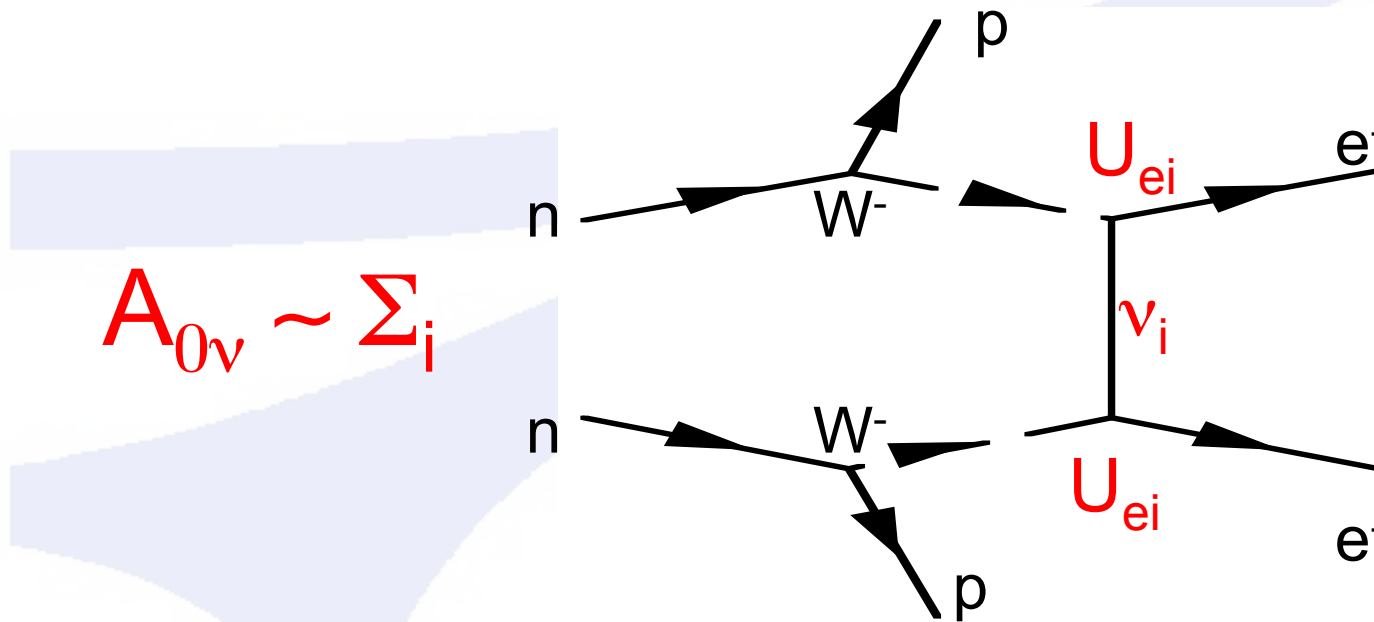
$\langle m_{\beta\beta} \rangle$ is the modulus of the resultant.

In this example, $\langle m_{\beta\beta} \rangle$ has a **min**. It cannot be 0.





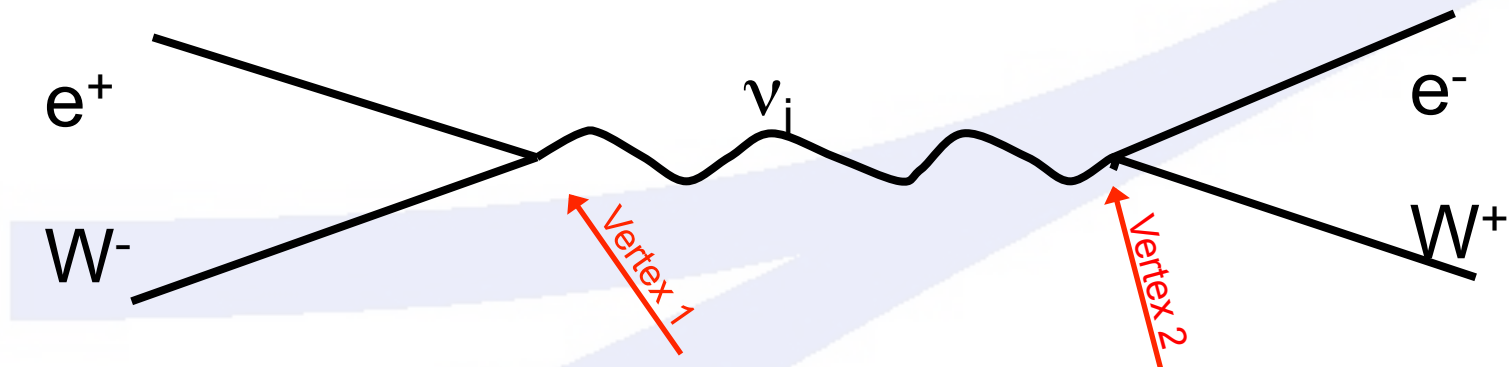
Why does the CP parity appear in $\langle m_{\beta\beta} \rangle$?



- Look at the critical part of this diagram.



The crossed channel.



$$A \propto \sum_i U_{ei}^2 \langle e^+ W^- | H_{SM} | \nu_i \rangle \langle \nu_i | H_{SM} | e^- W^+ \rangle$$

The 1st vertex creates the CP partner of the particle needed by the 2nd vertex.

$$\text{But } CP | \nu_i \rangle = \varepsilon_i | \nu_i \rangle$$

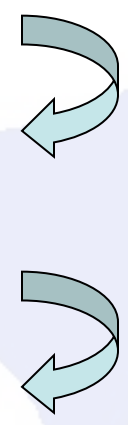
Upon substitution, the factor ε_i appears.

The importance of Majorana neutrinos and Lepton number conservation violation




Dirac Picture

A Dirac mass mixes these Helicity-related states

$$\begin{pmatrix} \nu_L \\ \nu_R \\ \bar{\nu}_R \\ \bar{\nu}_L \end{pmatrix}$$
Two curved arrows on the right side of the Dirac spinor column. The top arrow connects the ν_R and $\bar{\nu}_R$ components, and the bottom arrow connects the $\bar{\nu}_L$ and ν_L components, indicating the mixing of these states by a Dirac mass.

Majorana Picture

A Majorana mass mixes these Helicity-related states

$$\begin{pmatrix} \nu_L \\ \bar{\nu}_R \end{pmatrix} \quad \begin{pmatrix} \bar{\nu}_L \\ \nu_R \end{pmatrix}$$
Two curved arrows on the right side of the Majorana spinors. The top arrow connects the $\bar{\nu}_R$ component of the first spinor to the $\bar{\nu}_L$ component of the second spinor, and the bottom arrow connects the ν_R component of the second spinor to the ν_L component of the first spinor, indicating the mixing of these states by a Majorana mass.

**Majorana neutrinos
lead to Lepton number
violation**



All $\beta\beta$ transitions

Require Majorana mass to mix helicity states for non-zero rate

Standard Model
LHC vertices
(Similar for 2 RHC vertices)

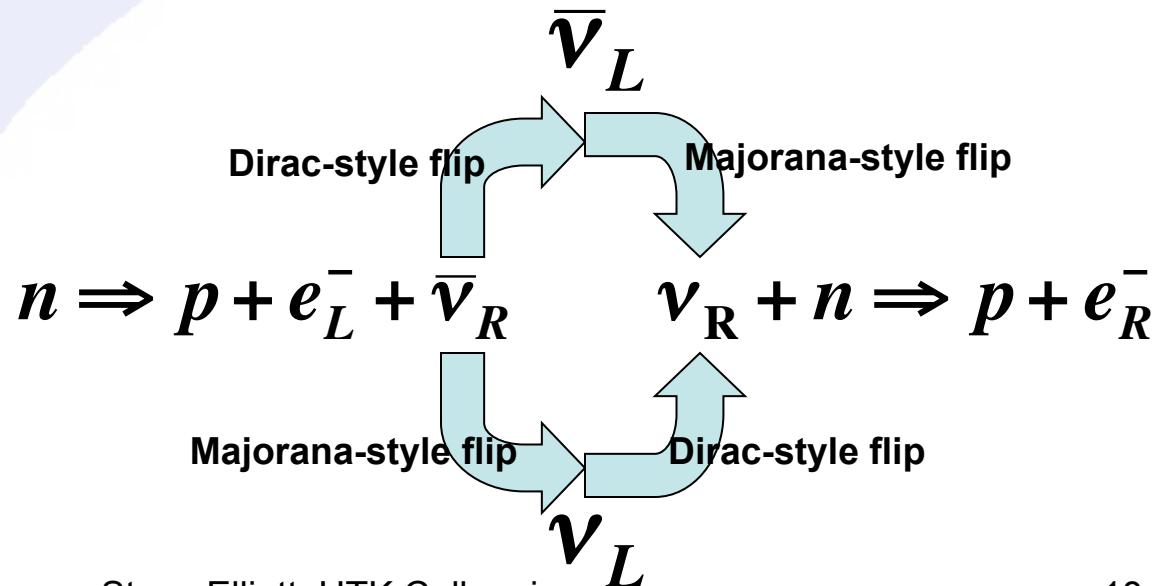
$$n \Rightarrow p + e_L^- + \bar{\nu}_R \quad \nu_L + n \Rightarrow p + e_L^-$$

Majorana-style helicity flip



LHC at 1st vertex
RHC at 2nd vertex

Again requires
Majorana mass



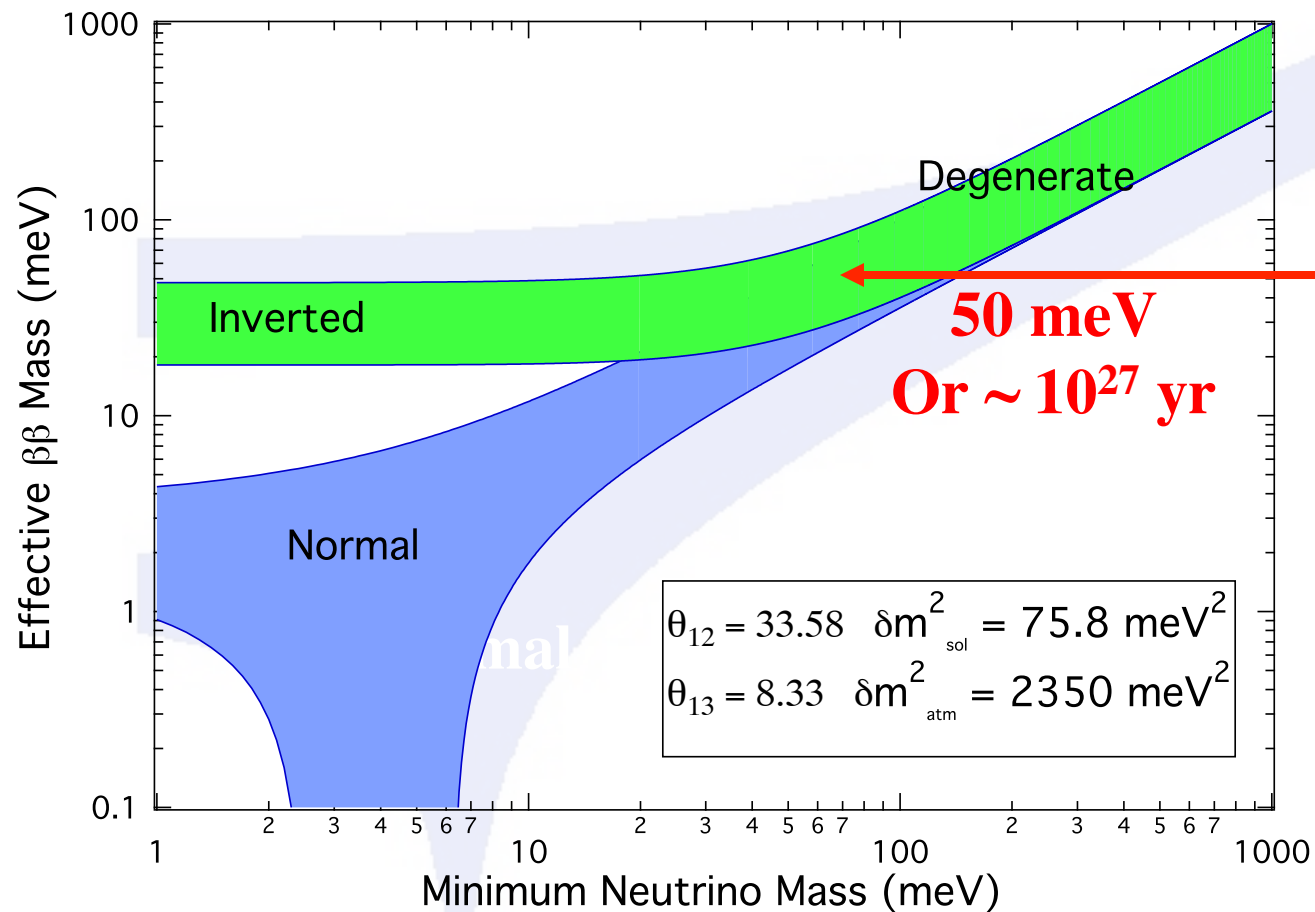


$\beta\beta$ and the neutrino

- $\beta\beta(0\nu)$ decay rate proportional to neutrino mass
 - Most sensitive technique (if Majorana particle)
- Decay can only occur if Lepton number conservation is violated
 - Leptogenesis?
- Decay can only occur if neutrinos are massive Majorana particles
 - Critical for understanding incorporation of mass into standard model
 - $\beta\beta$ is only practical experimental technique to answer this question
- Fundamental nuclear/particle physics process

$\beta\beta$ Sensitivity

(mixing parameters from arXiv:1106.6028)



Even a null result will constrain the possible mass spectrum possibilities!

A $m_{\beta\beta}$ limit of ~ 20 meV would exclude Majorana neutrinos in an inverted hierarchy.



$\beta\beta$ History

- $\beta\beta(2\nu)$ rate first calculated by Maria Goeppert-Mayer in 1935.
- First observed directly in 1987.
- Why so long? Background
 - $\tau_{1/2}(\text{U, Th}) \sim T_{\text{universe}}$
 - $\tau_{1/2}(\beta\beta(2\nu)) \sim 10^{10} T_{\text{universe}}$
- But next we want to look for a process with:
 - $\tau_{1/2}(\beta\beta(0\nu)) \sim 10^{17} T_{\text{universe}}$



$\beta\beta$ Candidates

There are a lot of them!

Hydrogen 1 1.00794																		Helium 2 4.00260			
Lithium 3 6.941		Beryllium 4 9.01218																		Neon 10 20.1797	
Sodium 11 22.98976928		Magnesium 12 24.304																		Argon 18 39.948	
Potassium 19 39.0983		Calcium 20 40.078		Scandium 21 44.955912	Titanium 22 47.88	Vanadium 23 50.9415	Chromium 24 51.9961	Manganese 25 54.938045	Iron 26 55.845	Cobalt 27 58.933195	Nickel 28 58.6934	Copper 29 63.546	Zinc 30 65.38	Gallium 31 69.723	Germanium 32 72.630	Arsenic 33 74.9216	Selenium 34 78.9718	Bromine 35 79.904	Krypton 36 83.80		
Rubidium 37 85.4678		Strontium 38 87.62		Yttrium 39 88.90584	Zirconium 40 91.224	Niobium 41 92.90638	Molybdenum 42 95.94	Technetium 43 [98]	Ruthenium 44 101.07	Rhodium 45 102.9055	Palladium 46 106.3676	Silver 47 107.8642	Cadmium 48 112.411	Indium 49 114.818	Tin 50 118.710	Antimony 51 121.757	Tellurium 52 127.60	Iodine 53 126.905	Xenon 54 131.29		
Cesium 55 132.90545196		Barium 56 137.327		Lanthanum 57 138.90547	Hafnium 72 178.49	Tantalum 73 180.94788	Tungsten 74 183.84	Rhenium 75 186.207	Osmium 76 190.23	Iridium 77 192.222	Pt 195.084	Au 196.966569	Hg 200.59	Tl 204.38	Pb 207.2	Bi 208.980399	Po [209]	At [210]	Rn [222]		
Francium 87 [223]		Radium 88 [226]																			
				La 138.90547	Ce 140.12	Pr 140.90765	Nd 144.242	Pm [144]	Sm 150.36	Eu 151.964	Gd 157.254	Tb 158.92534	Dy 162.5001	Ho 164.93032	Er 167.259	Tm 168.93274	Yb 173.05468				
				Ac [227]	Th 232.0377	Pa 231.03688	U 238.02891	Np [237]	Pu [244]	Am [243]	Cm [247]	Bk [247]	Cf [251]	Es [252]	Fm [257]	Md [258]	No [259]				



$\beta\beta$ Candidates

Abundance > 5%, Trans. Energy > 2 MeV

Hydrogen 1 H 1.00794																		Helium 2 He 4.00260																	
Lithium 3 Li 6.941		Beryllium 4 Be 9.0122																Boron 5 B 10.811		Carbon 6 C 12.011		Nitrogen 7 N 14.007		Oxygen 8 O 15.999		Fluorine 9 F 18.998		Neon 10 Ne 20.180							
Sodium 11 Na 22.990		Magnesium 12 Mg 24.305																Aluminum 13 Al 26.982		Silicon 14 Si 28.086		Phosphorus 15 P 30.974		Sulfur 16 S 32.065		Chlorine 17 Cl 35.453		Argon 18 Ar 39.948							
Potassium 19 K 39.098		Calcium 20 Ca 40.078		Scandium 21 Sc 44.956		Titanium 22 Ti 47.887		Vanadium 23 V 50.942		Chromium 24 Cr 51.996		Manganese 25 Mn 54.938		Iron 26 Fe 55.845		Cobalt 27 Co 58.933		Nickel 28 Ni 58.693		Copper 29 Cu 63.546		Zinc 30 Zn 65.38		Gallium 31 Ga 69.723		Germanium 32 Ge 72.630		Arsenic 33 As 74.922		Selenium 34 Se 78.96		Bromine 35 Br 79.904		Krypton 36 Kr 83.8	
Rubidium 37 Rb 85.468		Strontium 38 Sr 87.62		Yttrium 39 Y 88.906		Zirconium 40 Zr 91.224		Niobium 41 Nb 92.906		Molybdenum 42 Mo 95.94		Technetium 43 Tc [98]		Ruthenium 44 Ru 101.07		Rhodium 45 Rh 102.91		Palladium 46 Pd 106.42		Silver 47 Ag 107.87		Cadmium 48 Cd 112.41		Indium 49 In 114.82		Tin 50 Sn 118.71		Antimony 51 Sb 121.76		Tellurium 52 Te 127.6		Iodine 53 I 126.9		Xenon 54 Xe 131.3	
Cesium 55 Cs 132.91		Barium 56 Ba 137.33		Lanthanum 57 La 138.91		Hafnium 72 Hf 178.49		Tantalum 73 Ta 180.95		Tungsten 74 W 183.84		Rhenium 75 Re 186.21		Osmium 76 Os 190.23		Iridium 77 Ir 192.22		Platinum 78 Pt 195.08		Gold 79 Au 196.97		Mercury 80 Hg 200.59		Thallium 81 Tl 204.38		Lead 82 Pb 207.2		Bismuth 83 Bi 208.98		Polonium 84 Po [209]		Astatine 85 At [210]		Radon 86 Rn [222]	
Francium 87 Fr [223]		Radium 88 Ra [226]		Actinium 89 Ac [227]		Thorium 90 Th 232.04		Protactinium 91 Pa 231.04		Uranium 92 U 238.03		Neptunium 93 Np [237]		Plutonium 94 Pu [244]		Americium 95 Am [243]		Curium 96 Cm [247]		Berkelium 97 Bk [247]		Californium 98 Cf [251]		Einsteinium 99 Es [252]		Fermium 100 Fm [257]		Mendelevium 101 Md [258]		Nobelium 102 No [259]					

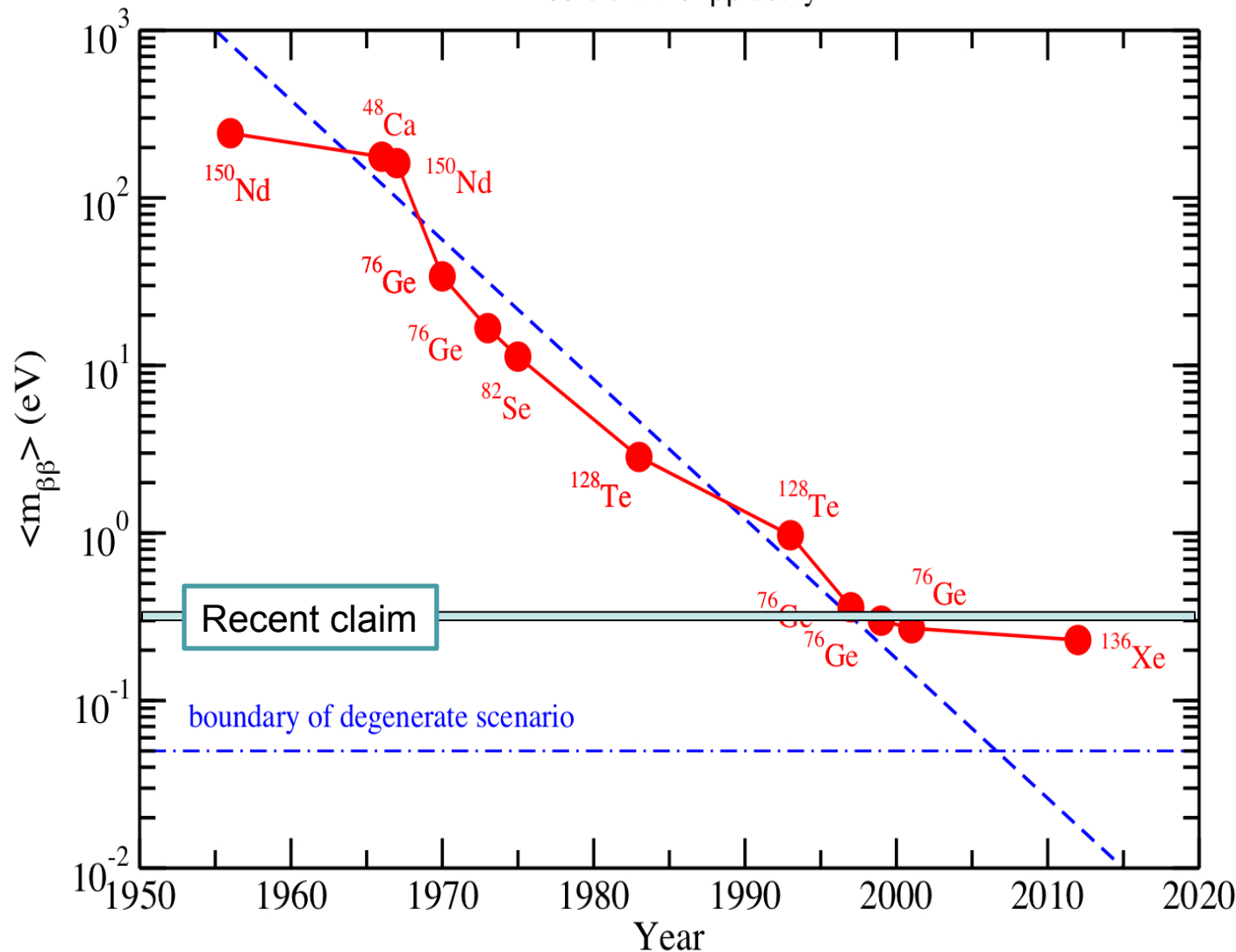
 Frequently studied isotope.

$\beta\beta$ trends (updated Elliott/Vogel plot by Vogel)



History of the $0\nu\beta\beta$ decay

Moore's law of $\beta\beta$ decay



Historically, there are > 100 experimental limits on $T_{1/2}$ of the $0\nu\beta\beta$ decay. Here are the records expressed as limits on $\langle m_{\beta\beta} \rangle$ using one set of nuclear matrix elements (RQRPA of Simkovic et al. 2009.) Note the approximate linear slope vs time on such semilog plot. However, during the last decade the complexity and cost of such experiments increased dramatically. The constant slope is no longer maintained.



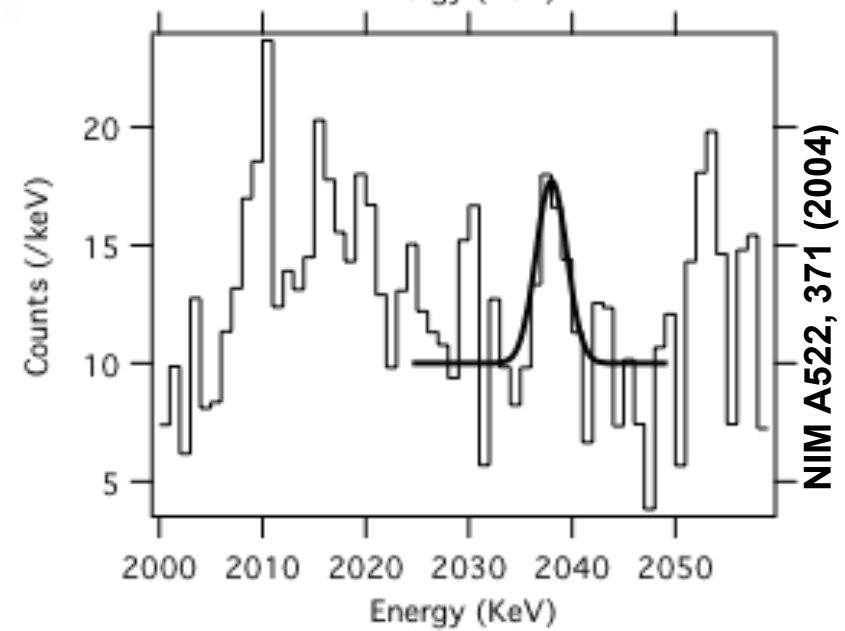
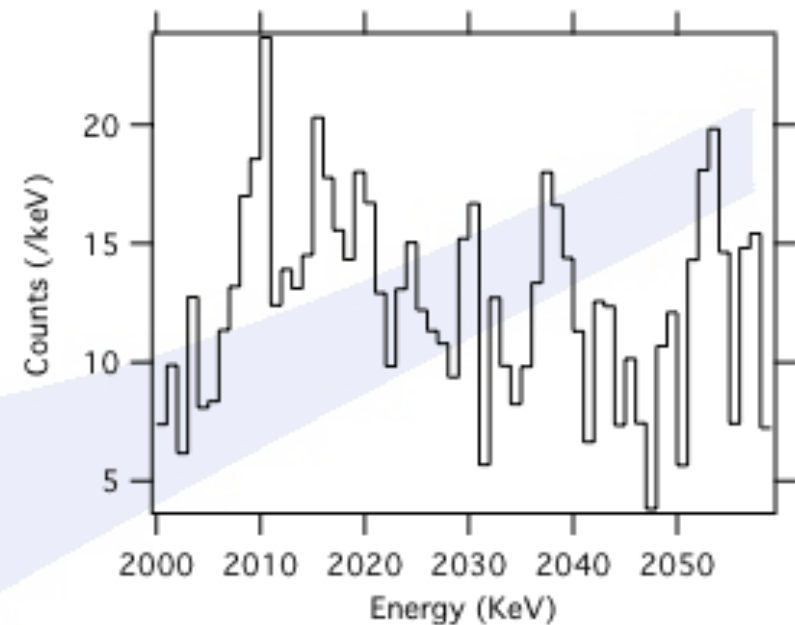
A Claim

has become a litmus test for
future efforts

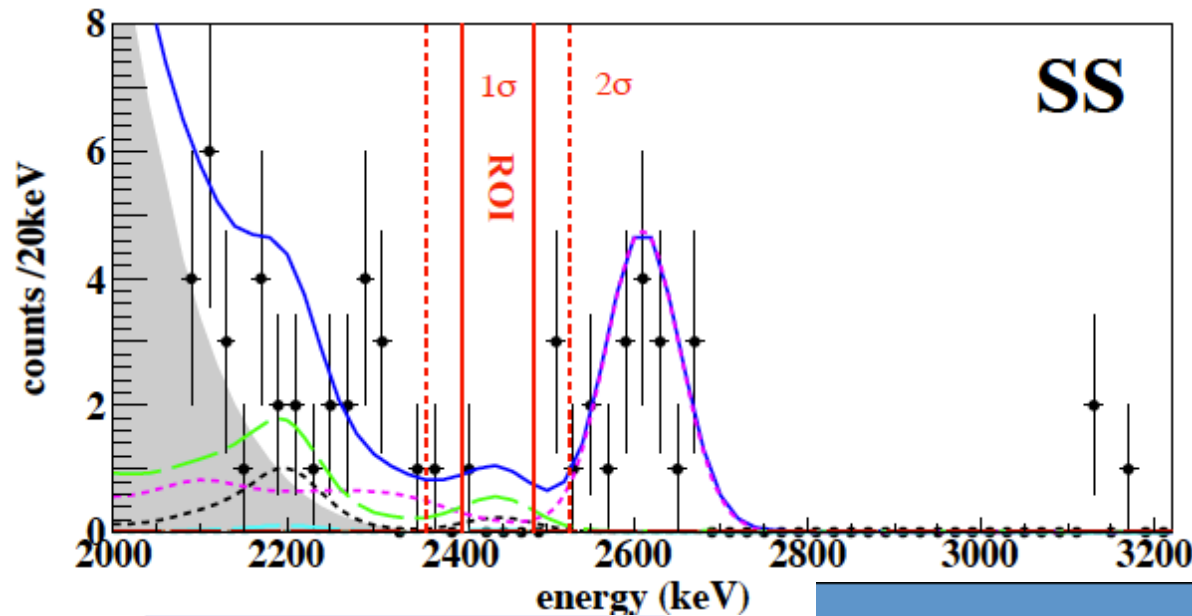
$\beta\beta$ is the search for a very
rare peak on a continuum
of background.

~70 kg-years of data
13 years

The “feature” at 2039 keV
is arguably present.



EXO result



Joint analysis with
KamLAND-Zen gives
 3.4×10^{25} y, 120-250 meV
arXiv:1211.3863

$T_{0\nu} > 1.6 \times 10^{25}$ y
 $m_{\beta\beta} < 140-380$ meV
120.7 days
79.4 kg ^{136}Xe
PRL 109, 032505

	Expected events from fit			
	$\pm 1 \sigma$		$\pm 2 \sigma$	
^{222}Rn in cryostat air-gap	1.9	± 0.2	2.9	± 0.3
^{238}U in LXe Vessel	0.9	± 0.2	1.3	± 0.3
^{232}Th in LXe Vessel	0.9	± 0.1	2.9	± 0.3
^{214}Bi on Cathode	0.2	± 0.01	0.3	± 0.02
All Others	~ 0.2		~ 0.2	
Total	4.1	± 0.3	7.5	± 0.5
Observed	1		5	
Background index b ($\text{kg}^{-1}\text{yr}^{-1}\text{keV}^{-1}$)	$1.5 \cdot 10^{-3} \pm 0.1$		$1.4 \cdot 10^{-3} \pm 0.1$	



Future Data Requirements

Why wasn't the claim sufficient to avoid controversy?

- **Low statistics of claimed signal - hard to repeat measurement**
- **Background model uncertainty**
- **Unidentified lines**
- **Insufficient auxiliary handles**

Result needs confirmation or repudiation



An Ideal Experiment

Maximize Rate/Minimize Background

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b\Delta E}{Mt_{live}} \right)^{\frac{1}{4}}$$

Large Mass (~ 1 ton)

Large Q value, fast $\beta\beta(0\nu)$

Good source radiopurity

Demonstrated technology

Ease of operation

Natural isotope

Small volume, source = detector

Good energy resolution

Slow $\beta\beta(2\nu)$ rate

Identify daughter in real time

Event reconstruction

Nuclear theory



Signal:Background ~ 1:1

Its all about the background

Half life (years)	~Signal (cnts/ton-year)	~Neutrino mass scale (meV)	
10^{25}	530	400	Degenerate
5×10^{26}	10	100	
5×10^{27}	To reach atmospheric scale need BG on order 1/t-y.	40	Atmospheric
$>10^{29}$		<10	Solar

Previous Background Levels



Experiment	Background (cnts/ ROI-t-y)	Width (1 FWHM)
IGEX	960 (400 with PSD)	4 keV ROI
Heid-Moscow	440 (50 with PSD)	4 keV ROI
CUORICINO	1440	8 keV ROI
GERDA	81 (no PSD)	4 keV ROI
EXO-200	130	106 keV ROI (1.8% 1 sig resol.)
KamLAND-Zen	~55(~2400per t(Xe))	Width not explicitly given

Background is per tonne of material – big difference for KamLAND-Zen



Background Considerations

At atmospheric scale, expect a signal rate on the order of 1 count/tonne-year

- $\beta\beta(2\nu)$
- natural occurring radioactive materials
- neutrons
- long-lived cosmogenics

Great Number of Proposed Experiments

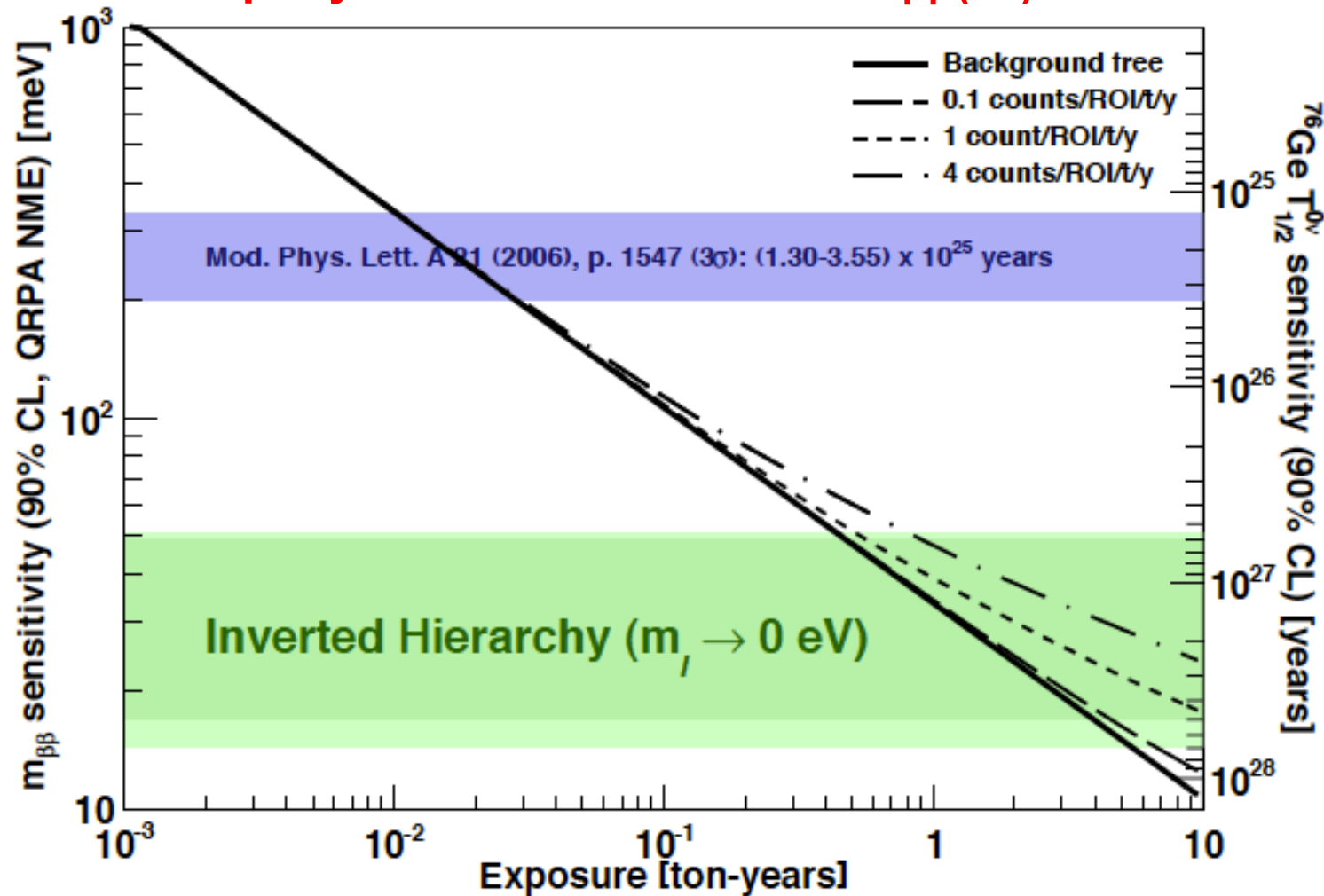
Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL	^{48}Ca	1 ton	CaF_2 scint. crystals	Development	Solotvina
LUCIFER	^{82}Se	18 kg	ZnSe scintillating bolometers	Development	Gran Sasso
Super					
Sup					
C					
M					
A					
Mo					
C					
C					
F					
Kam					
DCBA	^{229}Th	20 kg	^{229}Th ions and tracking	Development	Kamioka
SNO+[9]	^{150}Nd	43.7 kg	Nd loaded liq. scint.	Construction - 2013	SNOLab
GSO	^{160}Gd	2 ton	$\text{Gd}_2\text{SiO}_5:\text{Ce}$ crys. scint. in liq. scint.	Development	
Quantum Dots[8]	Various		Quantum Dots with isotope in liq. Scint.	Development	

- **Calorimeter**
 - Semi-conductors
 - Bolometers
 - Crystals/nanoparticles immersed in scintillator
- **Tracking**
 - Liquid or gas TPCs
 - Thin source with wire chamber or scintillator

Sensitivity, Background and Exposure



Goal is to achieve ultra-low backgrounds of less than 1 count per ton of material per year in the ROI about the $\beta\beta(0\nu)$ Q-value energy.





The MAJORANA Collaboration



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MAJORANA DEMONSTRATOR R&D Goals



- **Technical goals:**
 - Demonstrate backgrounds low enough to justify building a tonne scale Ge experiment.
 - Establish feasibility to construct & field modular arrays of Ge detectors.
 - Minimize costs, optimize the schedule, and retire risks for a future 1-tonne experiment.
- **Science goals:**
 - Although we are driven by technical goals, we also aim to extract the maximum science from the DEMONSTRATOR prototype,
 - Test the recent claim of an observation of $0\nu\beta\beta$ in ^{76}Ge .
 - Exploit the low-energy sensitivity to perform searches for dark matter, axions.
- **Work cooperatively with GERDA Collaboration toward a single international tonne-scale Ge experiment that combines the best features of MAJORANA and GERDA.**

The MAJORANA DEMONSTRATOR Module



^{76}Ge offers an excellent combination of capabilities & sensitivities.

(Excellent energy resolution, intrinsically clean detectors, commercial technologies, best $0\nu\beta\beta$ sensitivity to date)

- **40-kg of Ge detectors**

- 30-kg of 86% enriched ^{76}Ge crystals required for science and background goals
- Point-contact detectors for DEMONSTRATOR

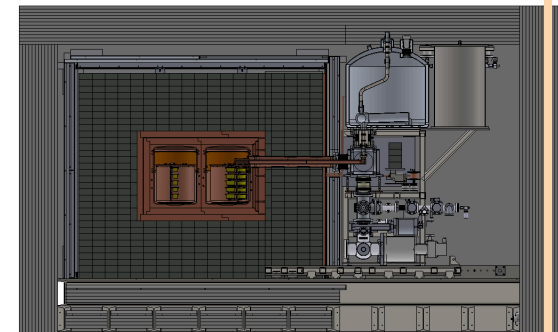
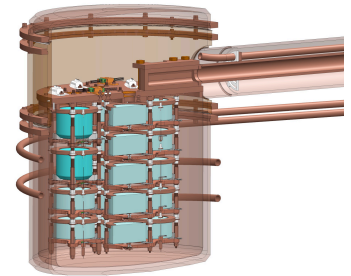
- **Low-background Cryostats & Shield**

- ultra-clean, electroformed Cu
- naturally scalable
- Compact low-background passive Cu and Pb shield with active muon veto

- **Located at 4850' level at Sanford Lab**

- **Background Goal in the $0\nu\beta\beta$ peak ROI(4 keV at 2039 keV)**

~ 3 count/ROI/t-y (after analysis cuts) (scales to 1 count/ROI/t-y for tonne expt.)

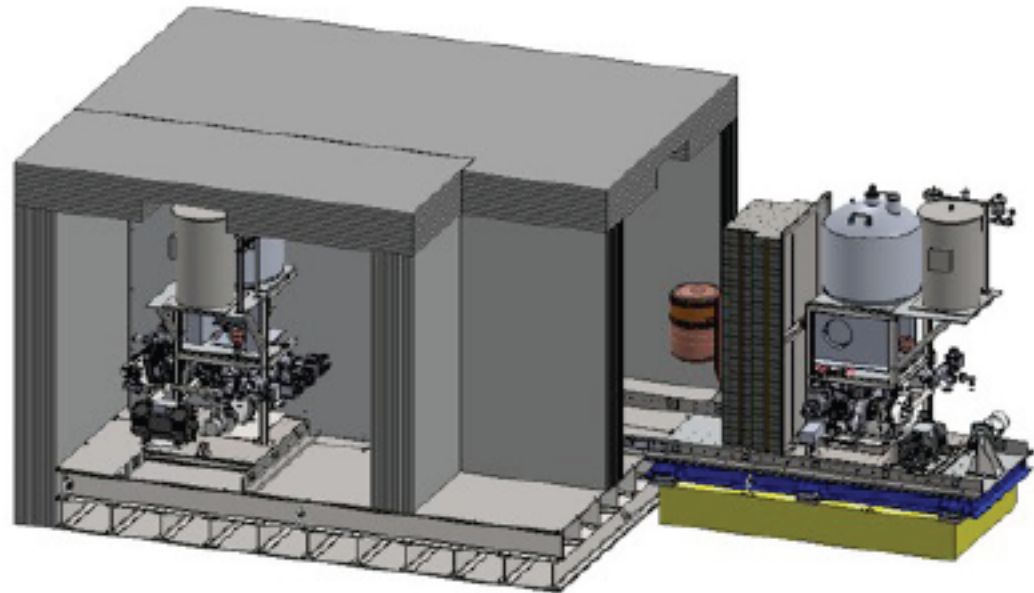
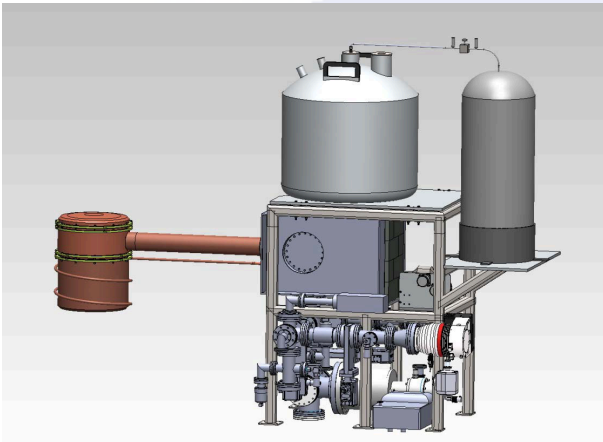


MJD Implementation



- **Three Phases**

- **Prototype cryostat (2 strings, $^{\text{nat}}\text{Ge}$)** (Spring 2013)
- **Cryostat 1 (3 strings $^{\text{enr}}\text{Ge}$ & 4 strings $^{\text{nat}}\text{Ge}$)** (Late 2013)
- **Cryostat 2 (up to 7 strings $^{\text{enr}}\text{Ge}$)** (Fall 2014)

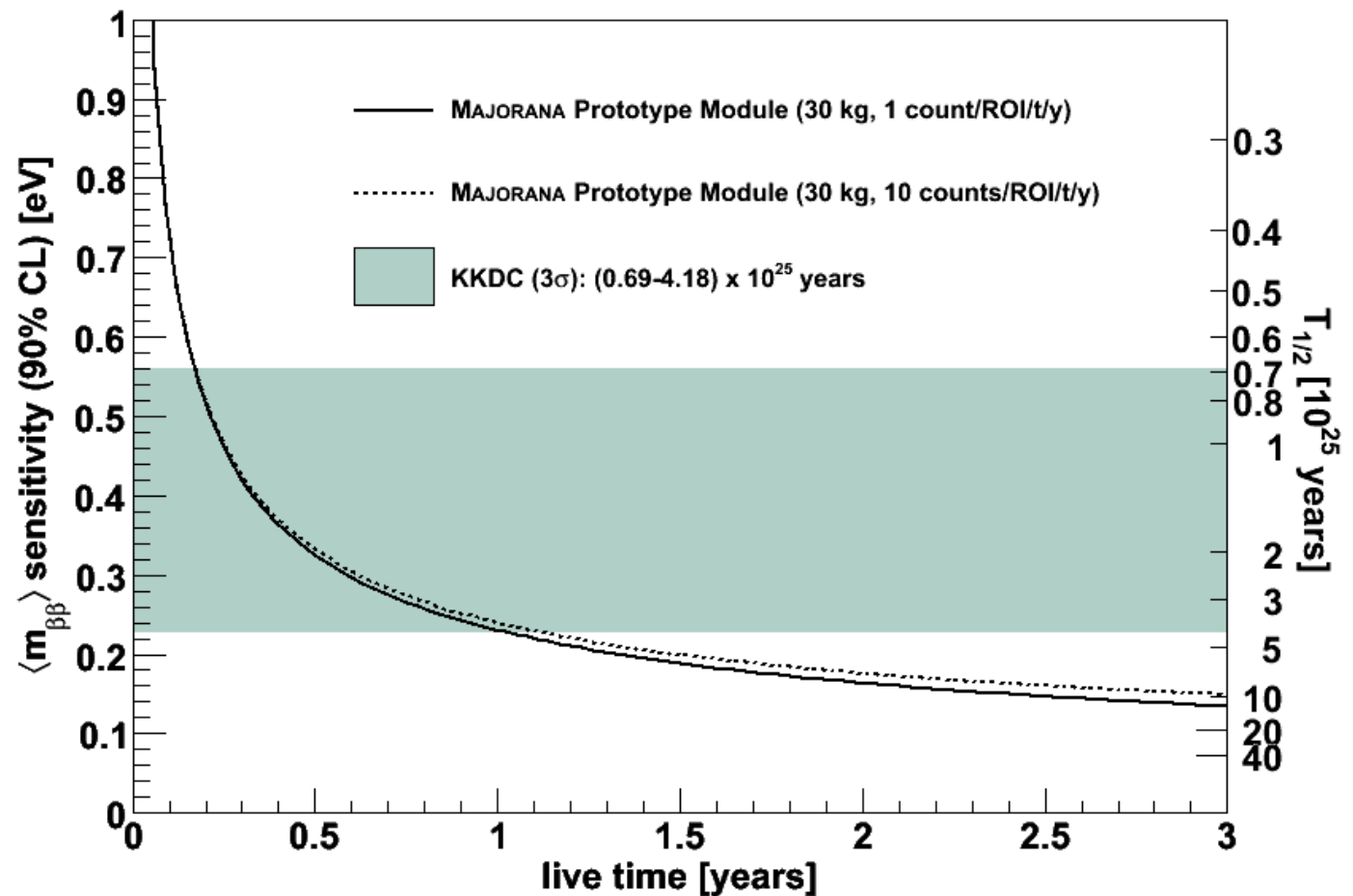




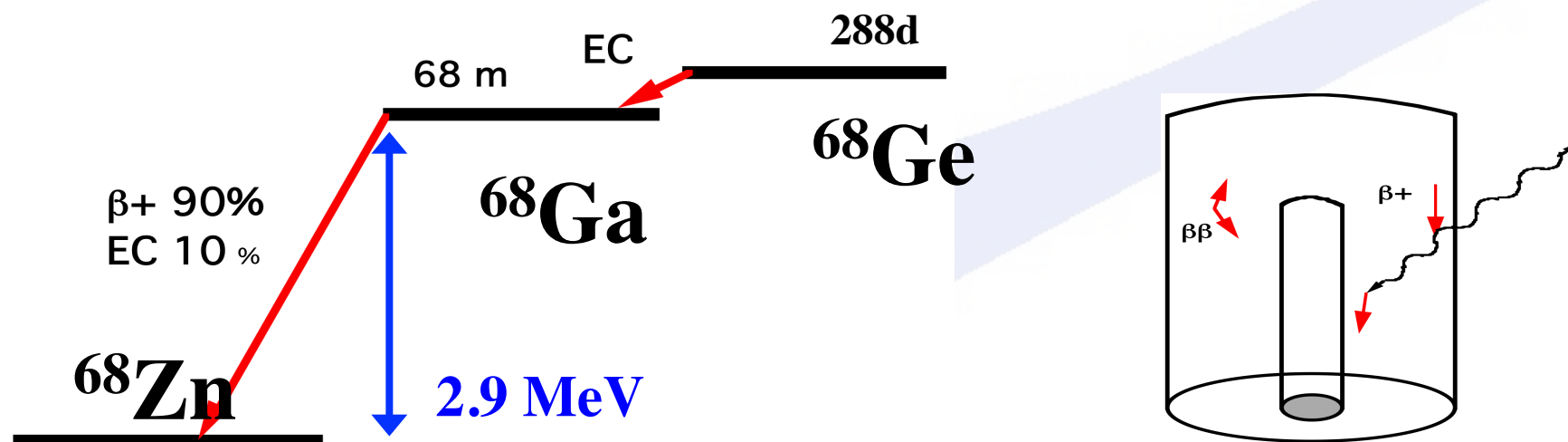
MAJORANA DEMONSTRATOR Module Sensitivity

- Expected Sensitivity to $0\nu\beta\beta$
(30 kg enriched material, running 3 years, or 0.09 t-y of ^{76}Ge exposure)

$T_{1/2} \geq 10^{26}$ y (90% CL). Sensitivity to $\langle m_{\nu} \rangle < 140$ meV (90% CL) [Rod05,err.]



Cosmogenic ^{68}Ge and ^{60}Co

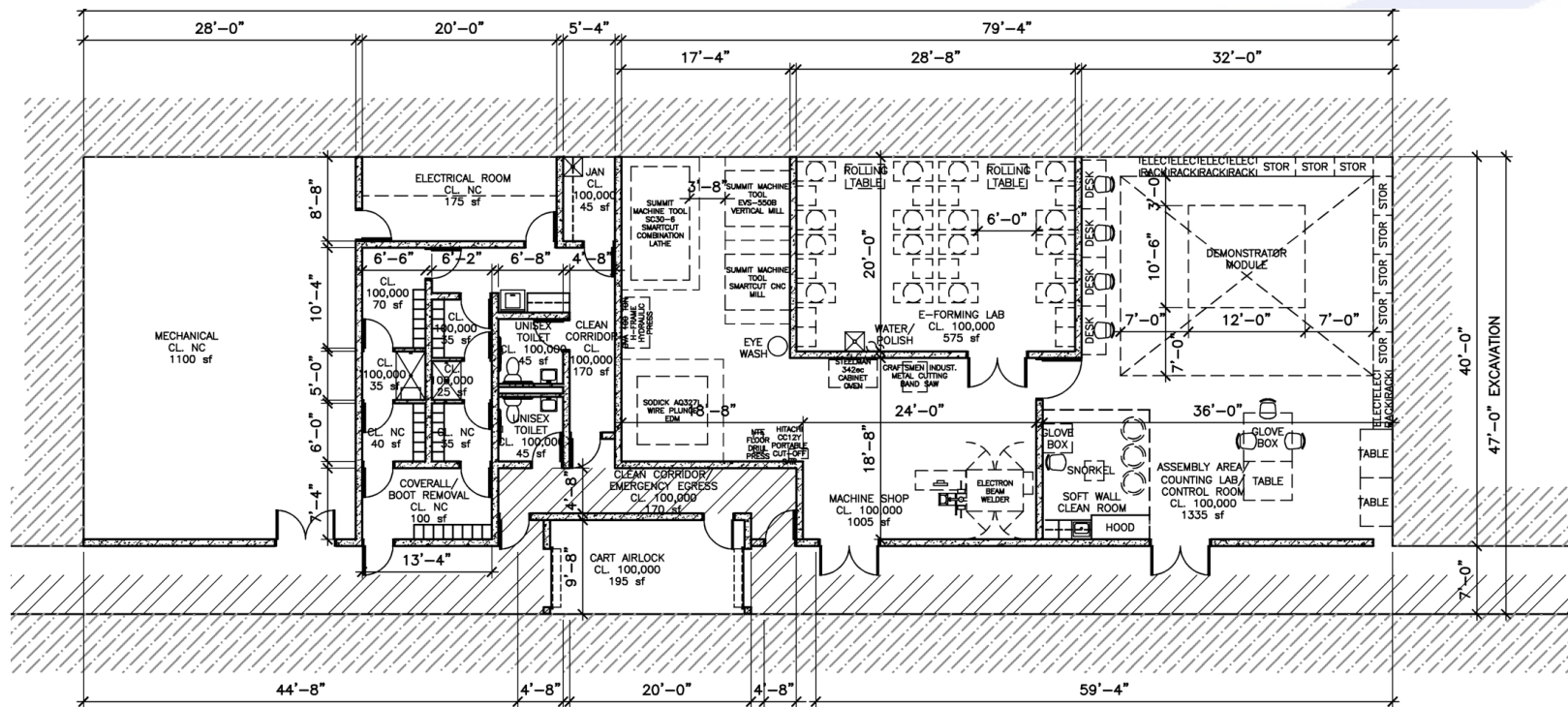


^{68}Ge and ^{60}Co are the dangerous internal backgrounds

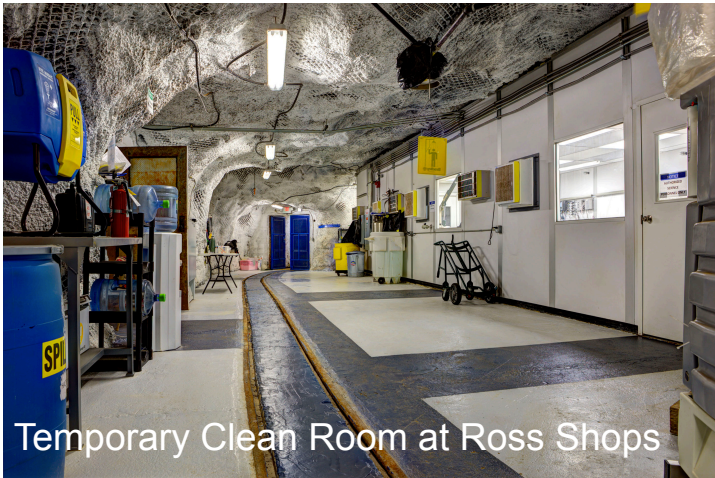
**For 60-kg enriched detector, initially
expect ~ 60 ^{68}Ge decays/day. $\tau_{1/2} = 288$ d**

Minimize exposure on surface during enrichment and fabrication
PSD, segmentation, time correlation cuts are effective at reducing these

Underground Laboratory



Underground Lab - Status

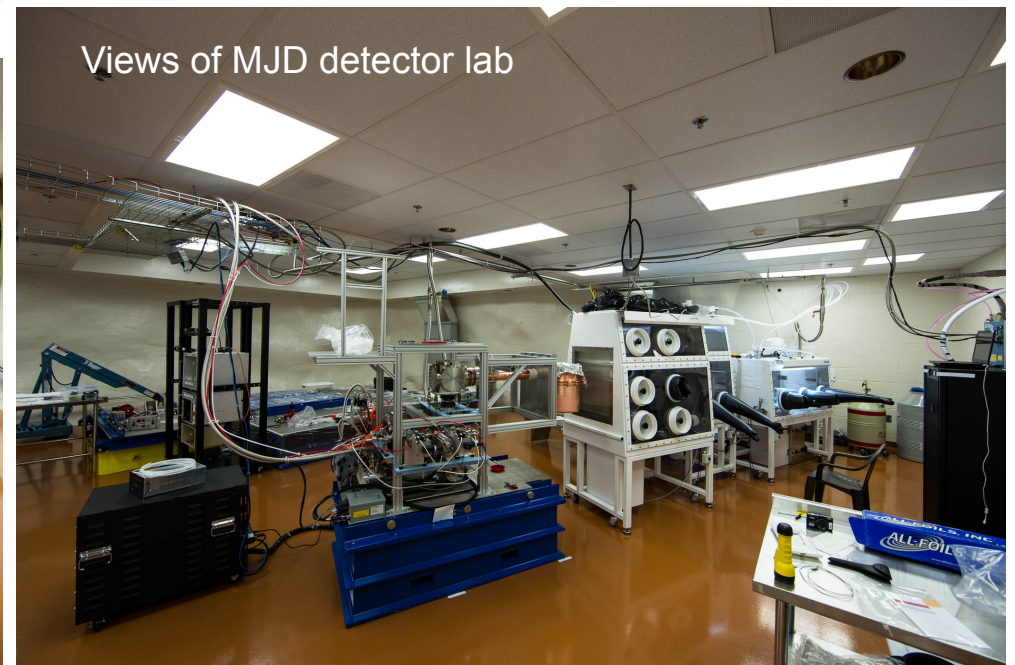


Temporary Clean Room at Ross Shops

- Eforming lab operational since summer 2011
- Davis Campus lab outfitting finished
- Shield floor, LN system, assembly table, air bearing system, glove boxes, localized clean space all installed



18 Dec. 2012



Views of MJD detector lab

Elliott, ER Review

Electroforming



Installation of mandrel in bath



- Eforming at PNNL and at 4850' at SURF
- Machine shop operational

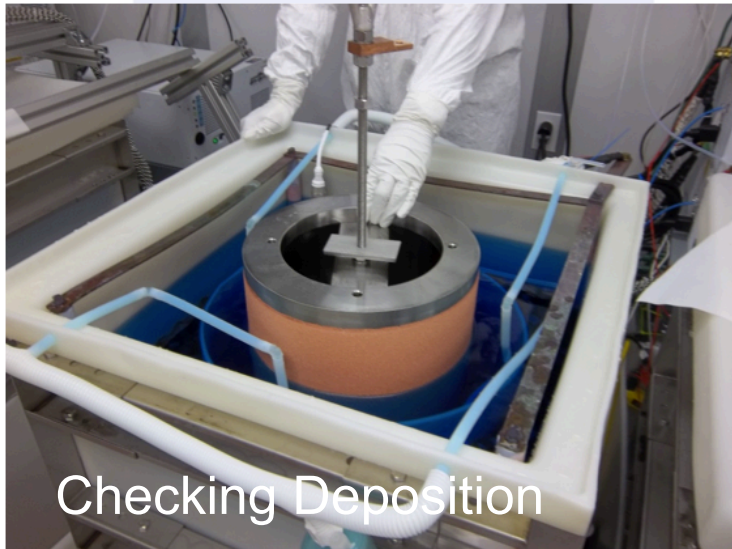
Copper ready to cut



EDM installed UG



Checking Deposition



Bake/Quench



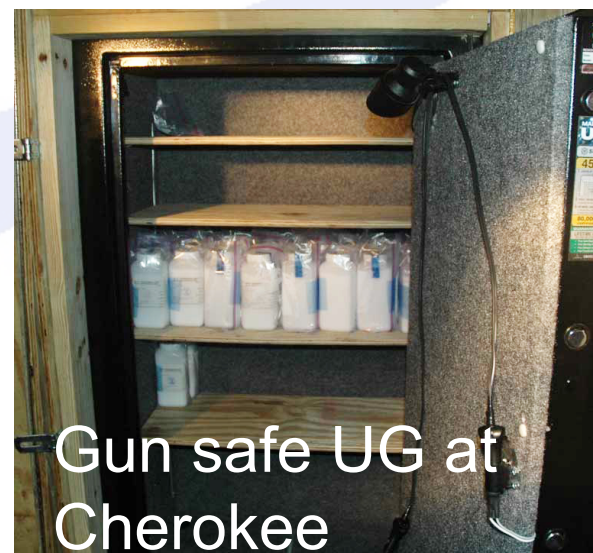
Lathe installed UG



Enriched Ge



- 42.5 kg ^{enr}Ge received as oxide and stored UG in Oak Ridge
- 4-5 kg Russian contribution



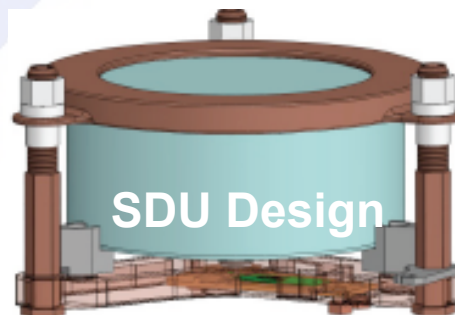
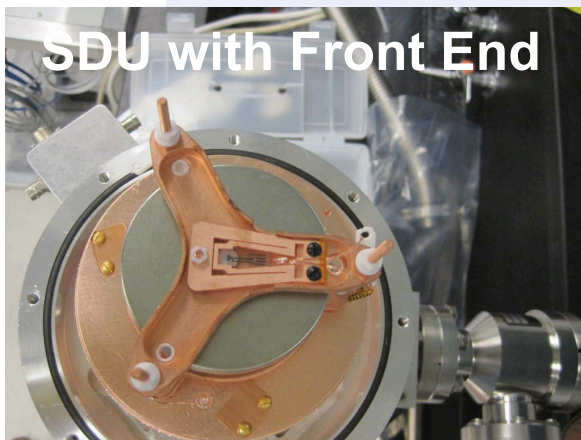
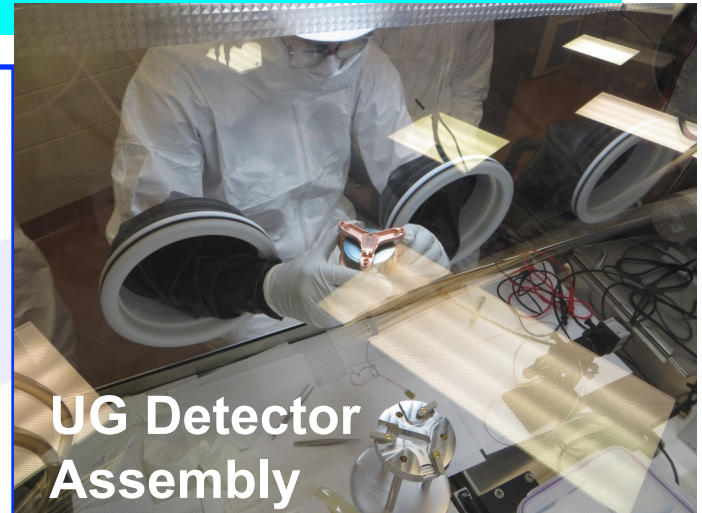
	Specs	ECP	ORNL Physics (Sample 1)	ORNL CSD (sample 2)	PNNL (Sample 3)
⁷⁶ Ge	≥86.0	87.67	86.9 (2)	87.9 (9)	88.2 (3)
⁷⁴ Ge		12.16	12.5 (1)	12.0 (1)	11.8 (3)
⁷³ Ge		0.07	< 0.2	0.052 (1)	0.04 (2)
⁷² Ge		0.05	<0.2	0.0058 (3)	0.02 (1)
⁷⁰ Ge	≤0.07	0.05	<0.2	0.0157 (3)	0.005 (4)



Detectors



- 20 kg of modified natural-Ge BEGe (Canberra) detectors in hand (33 dets. UG).
- ORTEC selected to produce enriched detectors. Excellent projected yield.
- First enriched detectors (5) delivered UG in February 2013.



Feb. 26, 2013

ORNL - Elliott

Modules



Thermosyphon System Parts

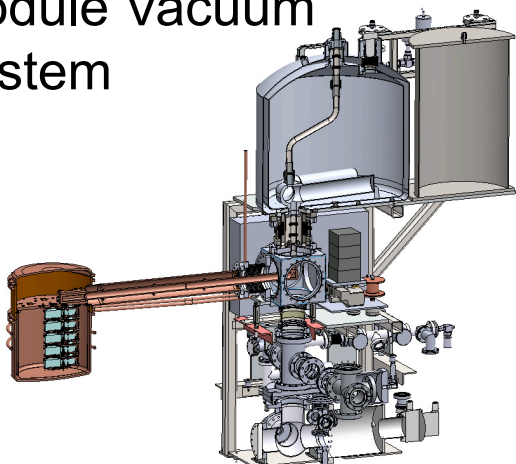


- Prototype cryostat being fabricated and assembled. E-beam welds completed
- Thermosyphon design validated. Fabricated and tested.
- Prototype vacuum system designed, reviewed, assembled, and being operated.
- String test cryostats built.
- Parts and material tracking in place.
- Clean machining implemented underground.

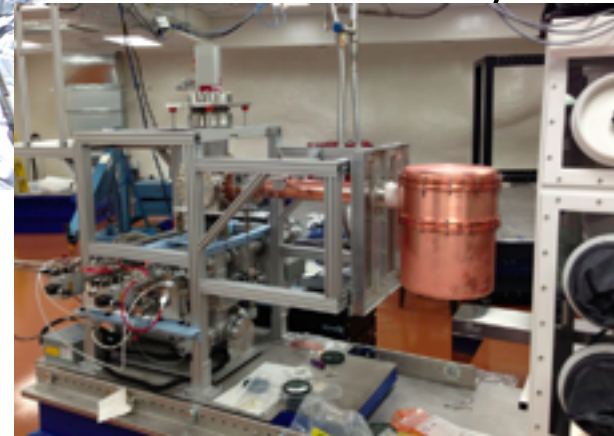
Cryostat hoop weld test



Module Vacuum System



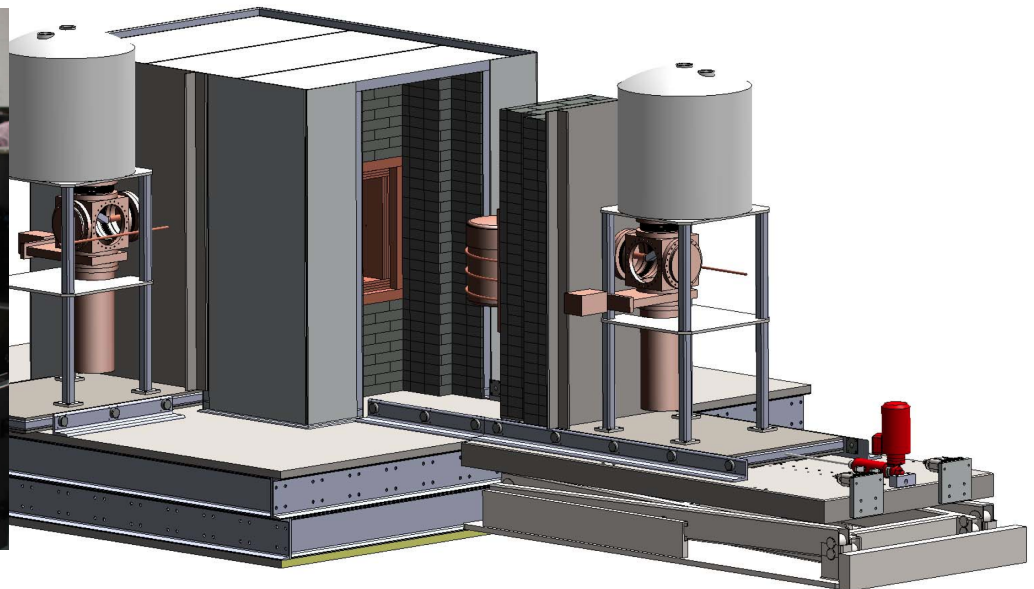
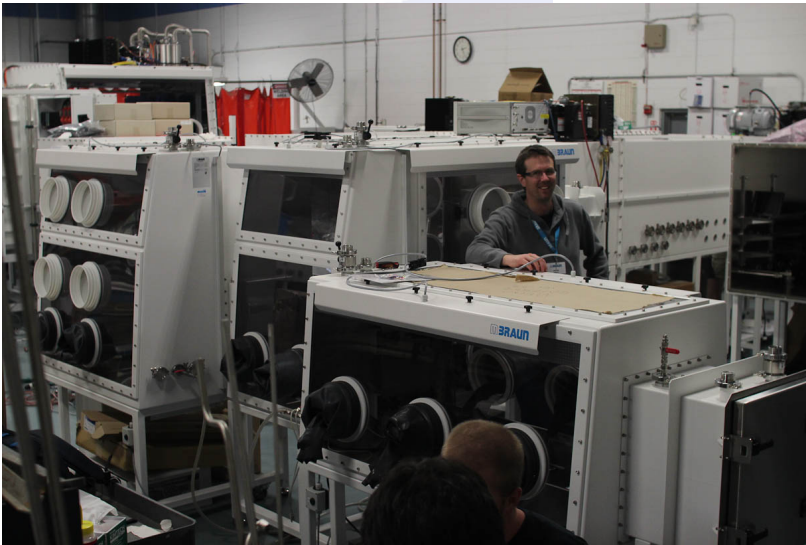
Prototype Module Vacuum System



Mechanical Systems



- Glove box (Mbraun) underground.
- Hovair delivered and tested.
- Overfloor installed UG.
- Majority of shielding material in hand, some is underground.
- Prototype calibration system demonstrated.

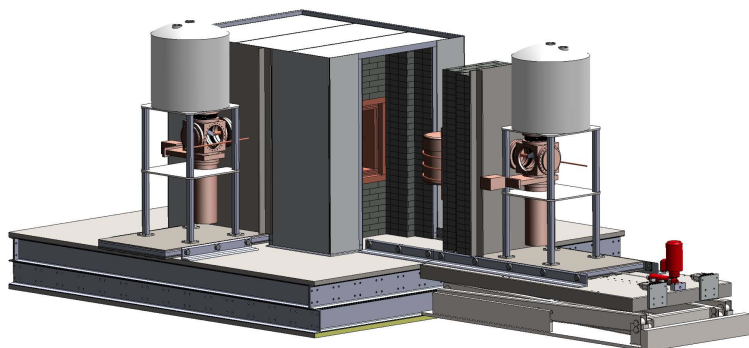


Feb. 26, 2013

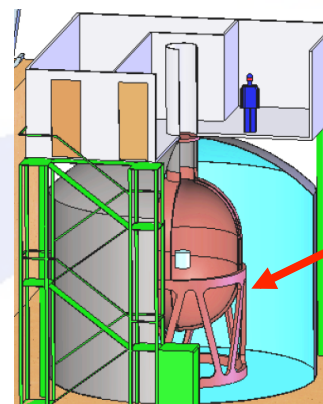
Towards 1TGe



MAJORANA



GERDA



- Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total ~40 kg (up to 30 kg enr.)
- 'Bare' ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I (2012): ~18 kg (HdM/IGEX diodes)
- Phase II (2013): add ~20 kg new detectors - Total ~40 kg

Joint Cooperative Agreement:

- Open exchange of knowledge & technologies (e.g. MaGe, R&D)
- Intention is to merge for tonne-scale experiment. Select best techniques developed and tested in GERDA and MAJORANA

MJD Overview



- Assembly and construction proceeding at Sanford Davis Campus laboratory.
- Based on assays, material backgrounds projected to meet cleanliness goals.
- EF copper being produced underground at SURF and PNNL
- Successful reduction and refinement of first 20 kg of ^{enr}Ge with 97.3% yield. Second batch purification underway.
- Detector vendor AMTEK (ORTEC) has produced detectors from the reduced/refined ^{enr}Ge . 5 underground at SURF.

Schedule

- Prototype Cryostat – Spring 2013
- Cryostat 1 – Late 2013
- Cryostat 2 - Fall 2014

